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海南岛热带原始森林主要分布区土壤有机碳密度及影响因素

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摘 要 以海南尖峰岭、霸王岭、五指山、吊罗山、鹦哥岭5个热带原始森林土壤为研究对象, 分层采集100 cm的土壤样品并分析有机碳含量, 用纵向拟合法和分层估算法分别估算其土壤有机碳密度及其影响因素。结果显示: (1)纵向拟合法计算的5个热带原始森林土壤有机碳密度分别为14.98、18.46、16.48、18.81、16.66 kg·m^{-2}, 分层估算法分别为14.73、16.24、15.50、16.91、15.03 kg·m^{-2}, 前者显著高于后者($p < 0.05$); 未经扰动的原始森林土壤, 宜采用纵向拟合法计算土壤有机碳密度。(2) 5个热带原始森林0–30 cm表层土壤有机碳含量分别占0–100 cm的50.50%、48.56%、43.49%、47.37、42.88%。(3)土壤有机碳密度与森林群落Shannon-Wiener指数($p < 0.01$)、Simpson指数($p < 0.05$)、物种丰富度($p < 0.01$)、土壤容重($p < 0.001$)存在极显著或显著的负相关关系; 与海拔($p < 0.05$)、土壤孔隙度($p < 0.001$)、土壤全氮含量($p < 0.001$)存在极显著或显著的正相关关系; 与坡向、林分生物量、平均胸径、平均树高无显著相关关系($p > 0.05$)。(4)由于海南地处低纬度地区, 其丰富的降水和持续高温条件加速了有机质的分解和物质的再循环, 导致海南森林土壤碳密度远低于全国平均水平。

关键词 海南热带原始森林; 土壤纵向拟合方法; 土壤分层方法; 土壤有机碳密度

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Soil organic carbon density and influencing factors in tropical virgin forests of Hainan Island, China

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Abstract

Aims Estimating soil organic carbon (SOC) density and influence factors of tropical virgin forests in Hainan Island provide new insight in basic data for SOC pool estimation and its dynamics study.

Methods The main distribution areas of tropical virgin forests in Jianfengling (JFL), Bawangling (BWL), Wuzhishan (WZS), Diaoluoshan (DLS), Yinggeling (YGL) of Hainan Island were selected, and soil samples (0–100 cm) were sampled and analyzed. SOC density was estimated by soil vertical fitting method and soil stratification method to discover the distribution characteristics of soil organic carbon in tropical virgin forests of Hainan Island.

Important findings Results showed that: (1) The average SOC density using soil vertical fitting method in JFL, BWL, WZS, DLS and YGL was 14.98, 18.46, 16.48, 18.81, 16.66 kg·m^{-2}, respectively, which was significantly higher ($p < 0.05$) than the estimated average SOC density using soil stratification method in these areas (14.73, 16.24, 15.50, 16.91, 15.03 kg·m^{-2}, respectively). It is better to use soil vertical fitting method for SOC density estimation when the soil was natural without disturbance. (2) The proportion of SOC content in the first 0–30 cm depth interval out of SOC in the whole 0–100 cm soil profiles in JFL, BWL, WZS, DLS and YGL was 50.50%,

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48.56%, 43.49%, 47.37%, 42.88%, respectively. (3) SOC density was significantly negative correlated with Shannon-Wiener index, Simpson index, species richness, and soil bulk density; and was significantly positive correlated with altitude, soil porosity, and soil nitrogen. However, SOC density was not significantly correlated to slope, biomass, average diameter at breast height, or average height. (4) Our study area Hainan was located in low latitude area with high rainfall and high temperature, which accelerated the decomposition of organic matter and nutrient recycling, resulting in significantly lower SOC densities in this tropical virgin forests of Hainan Island than the average value in China.

Key words Hainan tropical virgin forests; soil vertical fitting method; soil stratification method; soil organic carbon density

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森林生态系统作为陆地生态系统主体, 其面积仅占全球非冰表面的40% (徐新良等, 2007), 但维持着陆地生态系统植被碳库的82%–86%和土壤碳库的70%–73% (Schmidt *et al*., 2011; Todd-Brown *et al*., 2014), 总碳量高达638 Gt (1 Gt = 1 × 10^9 t) (FAO, 2010), 每年固定的碳约占整个陆地生态系统的2/3 (Fang & Chen, 2001)。森林土壤有机碳储量的变化影响着陆地生态系统碳收支平衡, 是导致大气碳库与全球气候变化主要的因素(Lal, 2005)。土壤碳库0.1%的变化将导致大气圈CO_2浓度发生百万分之一的变化, 全球土壤有机碳10%的变化, 相当于人类活动30年排放的CO_2量(Parker *et al*., 2001)。土壤有机碳作为一种稳定而长效的碳源物质, 其分布与动态变化是学者关注的热点问题(赵安玖等, 2009)。近年来, 我国在森林土壤有机碳密度的研究有增加趋势(王绍强和刘纪远, 2002), 但大都基于收集的资料, 在精度上有待提高。因此, 要更精准地评价土壤碳库, 须通过大量样地调查来实现。

海南热带森林占全国热带森林面积的31.4%, 是受全球气候变化影响的敏感区域, 在生态环境建设中起举足轻重的作用(蒋有绪和卢俊培, 1991)。一些学者对海南热带土壤碳密度进行了研究, 如王海燕等(2009)、谭丽霞等(2012)、李福燕等(2008)、陈小花等(2014)、曹启民等(2012)、张莉(2013), 但较少涉及原始森林土壤碳密度。本文以海南主要热带原始森林土壤为研究对象, 采用土壤纵向拟合法和土壤分层法分别计算土壤碳密度, 阐明其与地形、植被、土壤理化性质的关系, 为进一步精确估算海南岛热带原始林土壤碳库提供科学依据。

2 研究方法

2.1 研究地概况

研究地在海南岛热带原始森林主要分布区尖峰岭(JFL)、霸王岭(BWL)、五指山(WZS)、吊罗山(DLS)和鹦哥岭(YGL)。海南属低纬度热带岛屿季风气候, 雨热同期, 降水丰富, 干湿两季明显, 11月–翌年4月为旱季, 5–10月为雨季; 成土母岩主要是花岗岩、砂页岩和闪长岩等, 土壤主要为砖黄壤和砖红壤。各研究点基本情况见表1 (蒋有绪和卢俊培, 1991; 安树青等, 1999; 李意德等, 2002; 江海声, 2006; 王文进等, 2007; 龙文兴等, 2008; 臧润国, 2010; 黄运峰等, 2012; 刘惠宁和陈辈乐, 2012; 郝清玉等, 2013; 张晓琳等, 2014)。

2.2 样地设置、土壤采集及分析方法

在5个区域内各设置1 200 m^2 (30 m × 40 m)的典型样地30个, 记录其海拔、坡度、坡向等环境参数; 调查其树种组成、胸径(*DBH*)、树高等群落学参数, 并计算Shannon-Weinner指数和物种丰富度。样地内使用内径为3 cm的土钻随机选取4–6个点, 按0–10 cm、10–20 cm、20–30 cm、30–50 cm、50–100 cm等5个层次分别取样, 对应层次的样品进行混合。混合土样被带回实验室按四分法缩分再风干, 过2 mm筛后装瓶备测。土壤有机碳用重铬酸钾加热法, 土壤全氮用半微量开氏法, 土壤全磷用$HClO_4$- H_2SO_4法测定(史瑞和等, 1996; 鲁如坤, 2000)。在样地周边挖取代表性的一个土壤剖面(深100 cm), 用土壤环刀(100 cm^3)按上述土壤层次每层取2个环刀样品, 在105 ℃烘干至恒质量后称量, 并计算土壤容重。

群落Shannon-Wiener指数的计算:

表1 海南5个主要热带原始林区基本情况表
Table 1 Basic conditions of the five tropical virgin forests in Hainan

研究点 Location	经度 Longitude (E)	纬度 Latitude (N)	年平均气温 Mean annual temperature (℃)	平均年降水量 Mean annual precipitation (mm)	海拔范围 Elevation range (m)	主要森林类型 Main forest type	主要土壤类型 Main soil type
尖峰岭 Jianfengling	108.60°–109.08°	18.38°–18.83°	25–20	1 700–2 600	600–1 400	低地雨林、山地雨林 Lowland rainforest, Montane rainforest	砖红壤、砖黄壤 Latosol, lateritic yellow soil
霸王岭 Bawangling	108.97°–109.88°	18.88°–19.33°	25–20	1 500–2 300	600–1 500	低地雨林、山地雨林 Lowland rainforest, Montane rainforest	砖红壤、砖黄壤 Latosol, lateritic yellow soil
五指山 Wuzhishan	109.65° –109.78°	18.82° –18.97°	24–19	2 300–2 500	800–1 800	山地雨林、山地常绿阔叶林 Montane rainforest, montane broadleaved evergreen forest	砖黄壤、黄壤 lateritic yellow soil, yellow soil
吊罗山 Diaoluoshan	109.75° –110.05°	18.67° –18.97°	25–20	1 870–2 760	500–1 450	低地雨林、山地雨林 Lowland rainforest, Montane rainforest	砖红壤、砖黄壤 Latosol, lateritic yellow soil
鹦哥岭 Yinggeling	109.18°–109.57°	18.82°–19.13°	24–20	1 800–2 700	600–1 800	山地雨林、山地常绿阔叶林 Montane rainforest, montane broadleaved evergreen forest	砖红壤、砖黄壤、黄壤 Latosol, lateritic yellow soil, yellow soil

$$H' = -\sum_{i=1}^{S} p_i \ln p_i \tag{1}$$

式中S表示总物种数, p_i表示第i个种占总数的比例(Pielou, 1975)。

土壤容重的计算:

土壤容重$(\mathrm{g{\cdot}cm^{-3}}) = M/V$ (2)

式中M表示环刀内干土质量(g); V表示环刀体积(cm^3)。

2.3 土壤碳密度计算方法

土壤有机碳密度(SOC_{density})是指单位面积单位深度土体中土壤有机碳质量, 国际上通常以深度1 m、面积1 m^2, 即1 m^{3}的土壤有机碳质量为参照标准, 单位为kg C·m^{-2}。

2.3.1 纵向拟合法

纵向拟合方法是通过对土壤各层进行拟合得到土壤有机碳随深度变化的近似函数, 然后利用此函数计算平均土壤有机碳, 结合土壤质地、厚度、容重等来计算土壤有机碳密度。公式如下:

$$SOC_{\mathrm{density}} = C \times \theta \times D \times (1-\delta) / 100 \tag{3}$$

式中, C为平均土壤有机碳含量(g·kg^{-1}), D为土层厚度(cm), θ为土壤容重(g·cm^{-3}), δ为直径>2 mm的砾石含量(体积百分数)。土壤不同层次的有机碳含量、质地、容重等土壤理化性质也不同, 在数据允许的情况下, 应该分别计算, 但小区域范围内, 可以忽略砾石(粒径>2 mm)含量之间的差异(徐艳等, 2005)。根据研究区土壤质地(黄成敏和龚子同, 2000)及土壤石质度级别与δ的关系(姚贤良和程云生, 1986), 取δ值为0.5%。

表2 利用纵向拟合方法计算的各地区土壤有机碳含量、土壤容重和土壤有机碳密度
Table 2 The soil organic carbon (SOC) content, SOC density and soil bulk density measured by the vertical fitting method

地点 Location	土壤有机碳含量 SOC content (g·kg^{-1})	土壤容重 Soil bulk density (g·cm^{-3})	土壤有机碳密度 SOC density (g·kg^{-1})
尖峰岭 Jianfengling	11.32	1.33	14.98
霸王岭 Bawangling	14.84	1.25	18.46
五指山 Wuzhishan	13.58	1.22	16.48
吊罗山 Diaoluoshan	13.60	1.39	18.81
鹦哥岭 Yinggeling	16.26	1.03	16.66

2.3.2 分层估算法

土壤分层方法是将不同深度的土壤有机碳、容重进行加和, 然后再平均。根据土壤分层数据(表2)计算土壤有机碳密度, 公式如下:

$$SOC_{\mathrm{density}} = \sum_{i=1}^{5} C_i \times \theta_i \times D_i \times (1-\delta_i) / 100 \tag{4}$$

式中i为土层数, C、N、D、θ、δ的物理意义与公式3相同。

3 结果和分析

3.1 纵向拟合法计算土壤有机碳密度

利用土壤有机碳、土壤容重等数据拟合其随土壤深度变化情况。首先将各研究点的30个样点的土壤有机碳、土壤容重作出散点图, 然后利用线性函数、对数函数、幂函数、指数函数、二次多项式等多个函数进行拟合, 找出最佳的拟合曲线(图1和图2)。

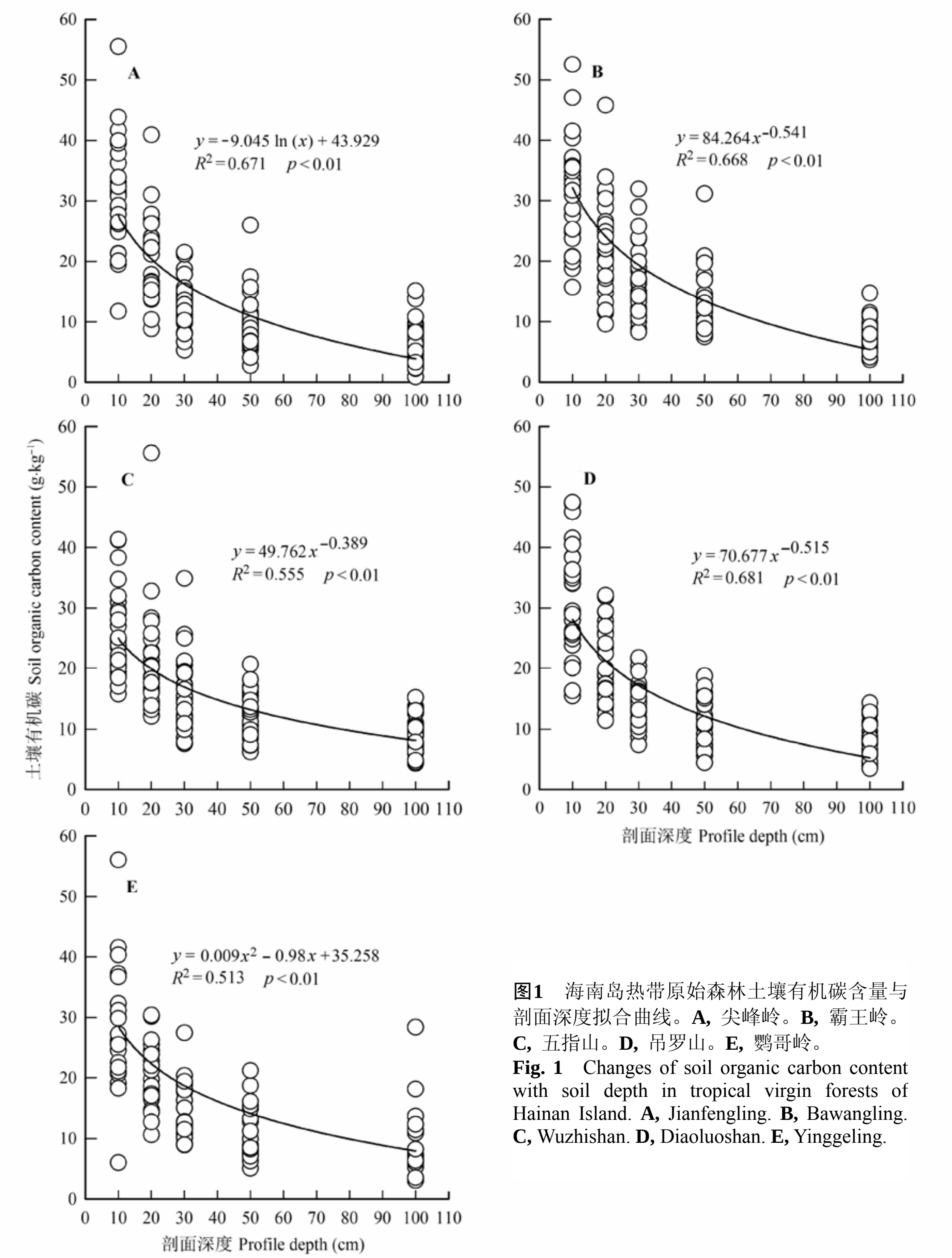

图1 海南岛热带原始森林土壤有机碳含量与剖面深度拟合曲线。**A,** 尖峰岭。**B,** 霸王岭。**C,** 五指山。**D,** 吊罗山。**E,** 鹦哥岭。

Fig. 1 Changes of soil organic carbon content with soil depth in tropical virgin forests of Hainan Island. **A,** Jianfengling. **B,** Bawangling. **C,** Wuzhishan. **D,** Diaoluoshan. **E,** Yinggeling.

根据拟合曲线和积分中值定理, 可得到5个地区的土壤有机碳密度、容重(表2), 其土壤容重的范围是1.03–1.39 g·cm^{-3}, 与全国平均容重1.30 g·cm^{-3}接近①。

① 郭沂林, 潘剑君 (2012). 寒温带与中亚热带森林土壤有机碳密度对比研究. 面向未来的土壤科学(上册)——中国土壤学会第十二次全国会员代表大会暨第九届海峡两岸土壤肥料学术交流研讨会论文集.

3.2 分层估算法计算土壤有机碳密度

对5个地区各层土壤有机碳、容重进行计算(表3), 其土壤表层有机碳(0–10 cm)显著高于其他土壤层次, 具有表聚性。

3.3 植被、地形和土壤主要性质与土壤碳密度的相关性

采用皮尔逊相关分析法, 分析5个研究区的植

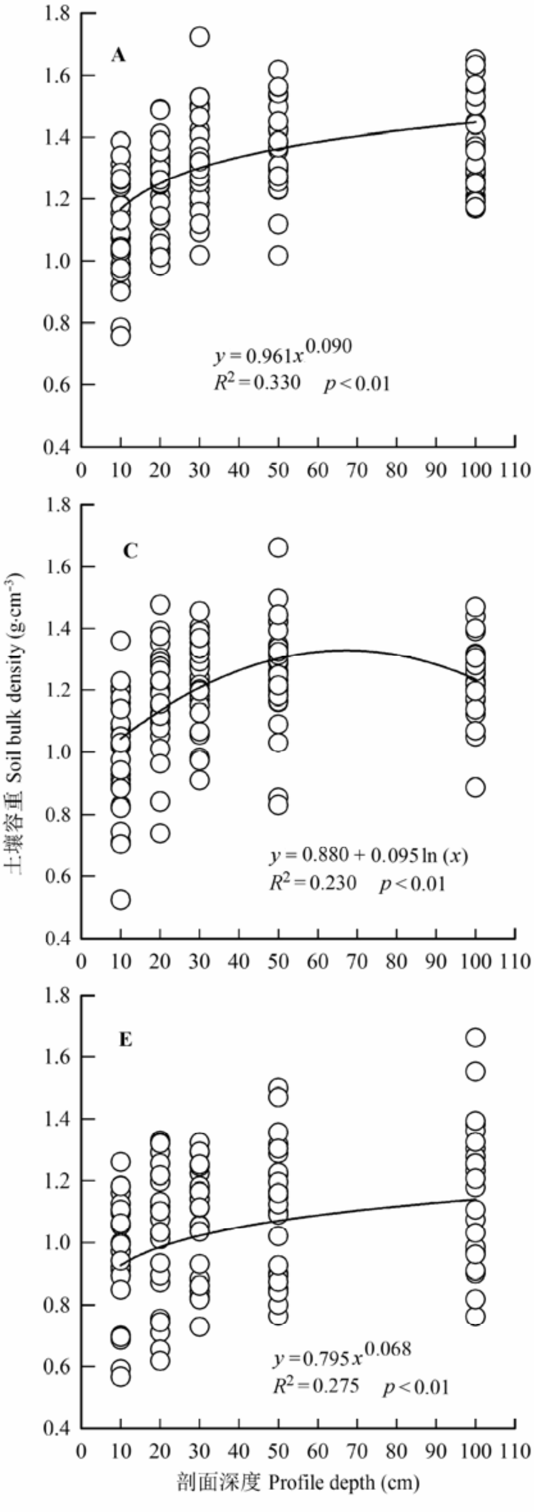

图2 海南岛热带原始森林土壤容重与剖面深度的拟合曲线。**A,** 尖峰岭。**B,** 霸王岭。**C,** 五指山。**D,** 吊罗山。**E,** 鹦哥岭。

Fig. 2 Changes of soil bulk density with soil depth in tropical virgin forests of Hainan Island. **A,** Jianfengling. **B,** Bawangling. **C,** Wuzhishan. **D,** Diaoluoshan. **E,** Yinggeling.

被因子(物种丰富度、Simpson指数、Shannon-Wiener指数、Pielou均匀度指数、林分生物量、林分郁闭度、林木平均高度、林木平均胸径和单位面积植株个体数)、地形因子(坡度、海拔、坡向)和土壤理化性质因子(土壤总孔隙度、土壤容重、土壤全氮、土壤全磷)与土壤有机碳密度的关系，表明Shannon-Wiener指数($r = -0.251$, $p < 0.01$)、Simpson指数($r = -0.182$, $p < 0.05$)、物种丰富度($r = -0.228$, $p < 0.01$)、土壤容重($r = -0.485$, $p < 0.001$)与土壤有机碳密度存在极显著或显著的负相关关系；海拔($r = 0.178$, $p < 0.05$)、土壤孔隙度($r = 0.485$, $p < 0.001$)、土壤全氮($r = 0.317$, $p < 0.001$)与土壤有机碳密度存在极显著或显著的正相关关系。经单因素方差分析，表明坡向对土壤有机碳密度无显著影响($F = 0.620$, $p > 0.05$)。

表3 各土壤层次的土壤有机碳含量(SOC, $g \cdot kg^{-1}$)和土壤容重(SBD, $g \cdot cm^{-3}$)的统计结果(平均值±标准误差)
Table 3 Soil organic carbon content (SOC, $g \cdot kg^{-1}$) and soil bulk density (SBD, $g \cdot cm^{-3}$) of all soil layers (mean ± SE)

土层 Soil layer (cm)	指标 index	尖峰岭 Jianfengling (n = 30)	霸王岭 Bawangling (n = 30)	五指山 Wuzhishan (n = 30)	吊罗山 Diaoluoshan (n = 30)	莺歌岭 Yinggeling (n = 30)
0–10	SOC	30.35 ± 1.57^{ABa}	34.71 ± 2.78^{Aa}	25.29 ± 1.27^{Ba}	30.95 ± 1.68^{Aa}	32.11 ± 2.13^{Aa}
	SBD	1.11 ± 0.03^{Aa}	0.99 ± 0.03^{Ba}	0.99 ± 0.03^{Ba}	1.16 ± 0.04^{Aa}	0.90 ± 0.04^{Ba}
10–20	SOC	19.54 ± 1.23^{Ab}	23.08 ± 1.41^{Ab}	20.88 ± 1.5^{Ab}	20.21 ± 1.16^{Ab}	20.79 ± 1.03^{Ab}
	SBD	1.24 ± 0.02^{ACb}	1.1 ± 0.03^{Bb}	1.16 ± 0.03^{ABb}	1.27 ± 0.03^{Cb}	1.00 ± 0.04^{Dab}
20–30	SOC	12.72 ± 0.68^{Ac}	16.37 ± 1.11^{ABc}	15.66 ± 1.09^{ABc}	14.08 ± 0.68^{Ac}	14.88 ± 0.83^{Ac}
	SBD	1.32 ± 0.03^{Abc}	1.22 ± 0.03^{Bc}	1.23 ± 0.02^{Bbc}	1.35 ± 0.04^{Ab}	1.02 ± 0.03^{Cb}
30–50	SOC	9.73 ± 0.83^{Ad}	12.42 ± 0.97^{Bc}	12.05 ± 0.67^{Bd}	10.41 ± 0.67^{ABd}	12.35 ± 0.89^{Bc}
	SBD	1.37 ± 0.03^{Ac}	1.27 ± 0.02^{Bcd}	1.26 ± 0.03^{Bc}	1.44 ± 0.02^{Ac}	1.06 ± 0.04^{Cb}
50–100	SOC	6.72 ± 0.61^{Ae}	7.87 ± 0.44^{ABd}	9.25 ± 0.50^{Bd}	8.22 ± 0.51^{ABd}	11.45 ± 1.28^{Cc}
	SBD	1.39 ± 0.03^{Ac}	1.32 ± 0.02^{Ad}	1.23 ± 0.02^{Bbc}	1.45 ± 0.03^{ACc}	1.05 ± 0.03^{Db}
0–100	$SOC_{density}$	14.73	16.24	15.50	16.91	15.03

不同大写字母表示各地区间的差异显著(p = 0.05), 不同小写字母表示不同土壤层次间的差异显著(p = 0.05)。$SOC_{density}$, 土壤有机碳密度。
Different capital letters showed significant difference among different areas (p = 0.05); Different lowercase letters showed significant difference among different soil layers (p = 0.05). $SOC_{density}$, soil organic carbon density.

PCA非约束排序分析(表4, 表5; 图3)表明, 前两轴解释总方差的比例是54.9%。从1型标尺双序图看, 物种丰富度, Shannon-Wiener指数, Simpson指数, Pielou均匀度指数, 生物量, 林木平均高度, 林木平均胸径, 郁闭度对排序空间的贡献大于所有变量的平均贡献。从2型标尺双序图看, 土壤有机碳密度、土壤总孔隙度、土壤全磷, 坡度、郁闭度, 土壤全氮, 单位面积植株个体数, 土壤容重, 物种丰富度对样方沿着第一轴分布起关键作用; 土壤有机碳密度与土壤总孔隙度、海拔、土壤全磷、坡度具有正相关关系, 与土壤容重、物种丰富度、Shannon-Wiener指数、Simpson指数具有负相关关系。

4 讨论和结论

4.1 土壤有机碳含量及碳密度

纵向拟合法计算的5个研究区土壤有机碳含量分别为11.32、14.84、13.58、13.60、16.26 $g \cdot kg^{-1}$, 土壤有机碳密度分别为15.21、18.60、16.08、18.81、16.66 $kg \cdot m^{-2}$。分层法计算的土壤有机碳密度分别为14.96、16.47、15.64、16.91、15.03 $kg \cdot m^{-2}$。两种方

表4 植被、地形和土壤主要性质第1、2、3、4主成分特征值、贡献率、累积率
Table 4 Eigenvalue, contributive and accumulative rates of principal component 1, 2, 3 and 4 in the vegetation, topography and soil properties

主成分 Component	特征值 Eigenvalue	贡献率 Contributive rate (%)	累计贡献率 Accumulative rate (%)
1	5.436 171	33.98	33.98
2	3.352 781	20.95	54.93
3	1.918 007	11.99	66.92
4	1.024 251	6.402	73.32

表5 植被、地形和土壤主要性质中第1、2、3、4主成分元素负荷量
Table 5 Element loading of principal component 1, 2, 3 and 4 in the vegetation, topography and soil properties

指标 Index	PC1	PC2	PC3	PC4
物种丰富度 Species richness	–0.361 22	–0.126 59	–0.193 71	0.173 50
Simpson指数 Simpson index	–0.245 99	–0.385 24	–0.159 24	–0.012 57
Shannon-Wiener指数 Shannon-Wiener index	–0.310 91	–0.338 54	–0.149 16	0.025 99
Pielou均匀度指数 Pielou evenness index	–0.130 10	–0.438 93	–0.163 01	–0.134 68
林分生物量 Forest biomass	0.174 37	–0.375 81	–0.076 67	0.092 61
林分郁闭度 Forest canopy density	0.328 61	–0.172 54	0.193 56	–0.102 91
林木平均树高 Trees average height	0.227 40	–0.357 66	0.171 44	–0.072 60
林木平均胸径 Trees average *DBH*	0.307 09	–0.324 36	0.066 92	–0.100 56
单位面积植株个体数 Plant individual numbers per unit area	–0.313 95	0.161 62	–0.265 97	0.280 35
坡度 Slope	0.081 52	–0.066 99	–0.227 18	0.199 30
海拔 Elevation	0.190 56	–0.222 59	–0.276 19	0.372 46
土壤总孔隙度 The soil total porosity	0.309 97	0.118 85	–0.361 86	0.077 20
土壤容重 Soil bulk density	–0.309 97	–0.118 85	0.361 86	–0.077 20
土壤有机碳 Soil organic carbon	0.143 54	0.112 50	–0.458 22	–0.363 67
土壤全氮 Soil total nitrogen	–0.035 58	0.034 16	–0.363 48	–0.579 54
土壤全磷 Soil total phosphorus	0.235 48	0.043 86	–0.092 07	0.423 42

DBH, diameter of breast height.

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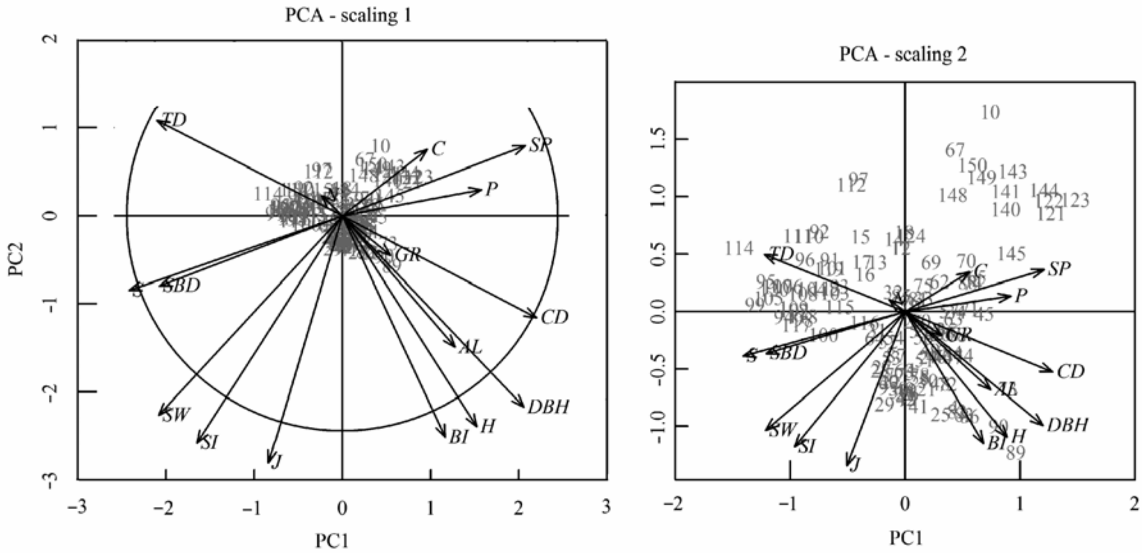

图3 海南岛热带原始森林植被、地形、土壤主要性质PCA双序图。*AL,* 海拔; *BI,* 生物量; *C,* 土壤有机碳密度; *CD,* 郁闭度; *DBH,* 林木平均胸径; *GR,* 坡度; *H,* 林木平均高度; *J,* Pielou均匀度指数; *N,* 土壤全氮; *P,* 土壤全磷; *S,* 物种丰富度; *SBD,* 土壤容重; *SI,* Simpson指数; *SP,* 土壤总孔隙度; *SW,* Shannon-Wiener指数; *TD,* 单位面积植株个数。

Fig. 3 The double sequence diagrams of principal component analysis in vegetation, topography, soil properties in tropical virgin forests of Hainan Island. *AL,* altitude; *BI,* biomass; *C,* soil organic carbon density; *CD,* canopy density; *DBH,* average tree diameter at breast height; *GR,* gradient; *H,* average tree height; *J,* Pielou evenness index; *N,* soil total nitrogen; *P,* soil total phosphorus; *S,* species richness; *SBD,* soil bulk density; *SI,* Simpson index; *SP,* soil porosity; *SW,* Shannon-Wiener index; *TD,* tree numbers in unit area.

法计算的森林土壤有机碳与海南白沙县原始森林土壤有机质A层为(41.8 ± 7.6) g·kg^{-1}, B层为(13.4 ± 4.2) g·kg^{-1} (王海燕等, 2009), 霸王岭热带低地雨林原始森林0–20 cm土壤有机质为31.869 g·kg^{-1} (黄永涛, 2013), 尖峰岭热带山地雨林原始森林0–10、10–30、30–60 cm土壤有机质分别为(57.31 ± 15.46)、(24.90 ± 7.06)、(13.10 ± 4.36) g·kg^{-1} (时雷雷, 2012)相一致, 均高于海南岛土壤有机碳密度的算术平均值9.48 kg·m^{-2} (李克让等, 2003)、广东鼎湖山自然保护区7.39 kg·m^{-2} (方运霆等, 2004)、中国土壤平均碳密度9.60 kg·m^{-2} (于东升等, 2005)和10.53 kg·m^{-2} (王绍强等, 2000)和全球土壤有机碳密度平均水平10.6 kg·m^{-2} (Batjes, 1996), 但小于东北地区平均土壤碳密度21.27 kg·m^{-2} (王绍强等, 2001)。但这些结果包括农地、林地、草地的总和, 不能反映森林土壤碳贮存的情况。因此, 专从森林角度来看, 海南5个地区原始林土壤有机碳密度小于中国森林土壤平均碳密度19.35 kg·m^{-2} (路秋玲等, 2012), 及方精云等(1996) (20.13 kg·m^{-2})、周玉荣等(2000) (19.36 kg·m^{-2})估算的全国森林土壤有机碳密度的平均值, 但高于广西(12.13 kg·m^{-2}) (蔡会德等, 2014)、美国大陆(10.8 kg·m^{-2})和澳大利亚(8.3 kg·m^{-2})的森林土壤有机碳密度(Dixon *et al*., 1994)。

海南岛森林土壤碳密度低于全国平均水平, 主要原因是海南岛地处低纬度地区, 丰富的降水和持续高温条件加速有机质的分解和物质的再循环, 不利于土壤有机碳的积累。但远远高于广西、美国和澳大利亚地区, 说明海南岛热带森林土壤有明显的固持有机碳能力, 在全球碳循环中是一个较大的碳汇。同时也高于鼎湖山近一倍, 其原因是鼎湖山土层较薄(平均为51.99 cm), 降雨量也较海南岛分配均匀, 全年高温高湿, 不利于有机碳的积累, 且人为收割林下层植物和凋落物造成土壤碳损失(方运霆等, 2004)。早在1988–1995年吴仲民(1997)的研究表明尖峰岭主要热带森林土壤有机碳储量为97.10–119.54 t·hm^{-2}, 加权平均值为102.60 t·hm^{-2}, 本文试验结果为152.0 t·hm^{-2}, 这与Zhou等(2006)研究发现的原始成龄林土壤碳库有累积现象是一致的。

4.2 土壤有机碳密度在土层中的垂直变化

5个研究区0–30 cm的土壤有机碳含量变化较大, 而30–100 cm土层变化较少, 其中0–30 cm土壤有机碳含量分别占0–100 cm土层的50.50%、48.56%、43.49%、47.37、42.88%。张晓琳等(2014)的研究0–30 cm土层的有机碳贡献率是46.77%。Baties (1996)的研究0–30 cm土壤碳贮量在全球各类型土壤中的平均贡献率为49%。赵广帅等(2014)的

研究0–40 cm土层土壤有机碳在黄河下游引黄灌区的贡献率是43.5%。李英升等(2014)的研究0–30 cm土层土壤有机碳密度在江西省4种森林类型的贡献率为50%左右。潘鹏等(2014)的研究0–30 cm土壤有机碳密度在江西中部马尾松(*Pinus massoniana*)天然林不同龄组的贡献率在41.3%–52.4%之间。Liu等(2012)的研究中0–20 cm土壤平均有机碳密度在青藏高原东北部7个植被类型的贡献率为43%。本文结果与上述一致。上层土壤有机碳密度明显高于下层, 主要因为土壤有机碳来源于地上的凋落物和地下的根系。凋落物集中在地表, 其分解产物向浅层土壤转移; 同时地下的根系也集中在浅层土壤。故浅层土壤有机碳密度的贡献率较高。

4.3 土壤有机碳密度的影响因素

海南岛热带原始林区土壤有机碳密度与Shannon-Wiener指数、Simpson指数、物种丰富度呈负相关关系。Roem等(2002)的研究表明物种多样性与土壤养分呈负相关关系。DiTommaso和Aarssen (1989)研究表明草本物种丰富度随土壤养分增加而降低。王长庭(2010)研究认为不同类型草地群落其多样性指数随土壤有机碳增加而降低。崔鸿侠等(2012)研究表明灌木层和草本层物种多样性与土壤碳储量显著负相关。肖德荣等(2008)研究认为Shannon-Wiener指数、Simpson指数与土壤有机质含量负相关。李林等(2006)研究表明灌木层的Shannon指数与土壤有机质显著负相关。在海南岛热带原始森林里, 物种数增多其根系分泌物及凋落物质量多样化, 这导致微生物数量和活性升高及土壤酶活性增强, 加速土壤有机物质的分解及养分元素的释放, 使得土壤有机碳密度随多样性增加减少。另外, 当土壤中养分丰富时, 一些物种对丰富的养分能很快地吸收和利用, 并且将形成占优势的区域而排除其他物种进入(Gough *et al*., 2000)。Xu等(2015)对尖峰岭热带雨林的研究表明稀有种往往分布在生物多样性较低的贫磷地方, 且本文研究结果为生物多样性与土壤有机碳密度负相关, 故稀有种分布的地方土壤有机碳密度可能较高, 因此, 这更加支持了划分自然保护区应包含生物多样性低的地方。本研究表明土壤有机碳密度与土壤容重负相关。在高寒草地(杜慧平, 2007)、高寒牧区(土壤活性有机碳) (展争艳等, 2005)、云南热区4种林分(陈伟等, 2013)、密云水库上游流域(王淑芳, 2012)等地土壤有机碳密度与土壤容重负相关关系。在影响土壤有机碳密度各因子中, 土壤容重的独立解释能力最强(42.0%), 土壤容重增加, 提高了土壤紧实度, 孔隙减少, 不利于有机碳矿化和分解(李志洪和王淑华, 2000)。

土壤有机碳含量随海拔上升而递增。在老哈河流域(郭月峰等, 2014)、密云水库上游流域(王淑芳等, 2012)、粤北亚热带山地森林(柯娴氡等, 2012)、庐山(杜有新等, 2011)、祁连山北坡垂直带山地森林(胡启武等, 2006)和其他地方(徐侠等, 2008; Fu *et al*., 2011; 耿广坡等, 2011)的研究土壤有机碳随海拔上升也递增。海拔升高导致气温降低, 蒸发量减少, 动植物残体分解缓慢且大部分沉积在土壤中, 使土壤有机碳的释放降低(杜有新等, 2011)。低海拔由于温度较高导致土壤有机碳分解加快, 促进了有机碳的释放(施政等, 2008)。

森林碳汇是当今应对全球气候变暖的积极措施, 也是林业对社会经济可持续发展做出贡献的途径和平台。海南是林业大省, 开展森林碳汇研究具有生态区位的重要优势, 通过精准测算和实地研究表明海南热带原始土壤有机碳密度较大, 有明显的蓄积能力, 是一个较大的碳汇。

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